AFRL-RW-EG-TR-2012-050

Increasing the Utility of the Copper Cylinder Expansion Test

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April 2012

Interim Report

AIR FORCE RESEARCH LABORATORY, MUNITIONS DIRECTORATE

Air Force Materiel Command ■ United States Air Force ■ Eglin Air Force Base

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
04-2012	Interim	1 October 2007 – 15 October 2010

4. TITLE AND SUBTITLE
Increasing the Utility of the Copper Cylinder Expansion Test

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
C. Michael Lindsay, George C. Butler, Chad G. Rumchik, Ben Schulze, Ryan Gustafson, Warren R. Maines

5d. PROJECT NUMBER
4347

5e. TASK NUMBER
95

5f. WORK UNIT NUMBER
05

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Munitions Directorate
Ordnance Division
Energetic Materials Branch
Eglin AFB, FL 32542-5910

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RW-EG-TR-2012-050

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory, Munitions Directorate
Ordnance Division
Energetic Materials Branch (AFRL/RWME)
Eglin AFB FL 32542-5910
Technical Advisor: Dr. Jennifer L. Jordan

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL-RW-EG

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RW-EG-TR-2012-050

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A: Approved for public release; distribution unlimited. Approval Confirmation 96 ABW/PA # 96ABW-2010-0539, dated October 15, 2010

13. SUPPLEMENTARY NOTES
DISTRIBUTION STATEMENT INDICATING AUTHORIZED ACCESS IS ON THE COVER PAGE AND BLOCK 12 OF THIS FORM.

14. ABSTRACT
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15. SUBJECT TERMS
cylinder test, CYLEX, hydrocode, high explosives, liners, Gurney

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			C. Michael Lindsay
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	14	**19b. TELEPHONE NUMBER** *(include area code)* 850-882-1543

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Propellants,
Explosives,
Pyrotechnics

Full Paper

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Received: June 3, 2010; revised version: August 2, 2010

DOI: 10.1002/prep.201000072

Abstract

We report the development of a new methodology for analyzing CYLEX tests streak images. In these tests, the displacement of the wall of an explosive filled cylinder is obtained by back-lighting the cylinder. The profile is imaged through a slit and streaked across a film record as the cylinder is detonated. A critical step in processing this data is the spatial calibration of the film and extraction of the profile of the cylinder from the image. Historically this has been a tedious task as it was performed by eye with the assistance of an optical comparator. Recently we developed an algorithm which automates the data calibration and extraction process of digitized streak records utilizing the Shen-Castan edge detection algorithm and the image processing capabilities found in the IGOR PRO software. The new processing methodology greatly increases the resolution of the data, removes human subjectivity, and reduces analysis time from hours to seconds. The higher resolution of the new method has enabled much greater accuracy in measuring early-time (<15 μs) expansion. With the aid of CTH hydrocode calculations, new fitting functions were developed to model both the early and late-time expansion data. These functions contain physically meaningful fitting parameters and include terms which mimic the intensity and time scales of the shock and gas induced expansion of the cylinder independently. We demonstrate the methodology and hydrocode calculations on a recent CYLEX test series aimed at examining the effects of a plastic liner on high-purity oxygen-free copper cylinders filled with a high explosive.

Keywords: Cylinder Test, CYLEX, Gurney, High Explosives, Hydrocode, Liners

1 Introduction

The Cylinder Expansion test (also known as the Cylinder test or CYLEX test) is a reliable and representative measure of an explosive's ability to accelerate metal. Initially developed by Lawrence Radiation Lab in the early 1960s [1,2], the test measures the displacement of the wall of an explosive filled cylinder as a function of time after initiation by recording its backlit silhouette with a streak camera. Owing to its relative simplicity and utility, the test has been used extensively in laboratories around the world, and a standardized procedure for performing the test and analyzing the data is described in the original US military standards on explosives qualification [3, 4].

The data extracted from the CYLEX test has long been used to determine the Jones-Wilkins-Lee equation of state (EoS) coefficients [5–7] and Gurney energies [8,9], each of which are helpful in characterizing the performance of an explosive. The useful parameters from the test are the velocity at 2 and 7 volume expansions (for EoS) and the maximum lateral velocity (for Gurney energy). Empirical fitting functions are usually used to smooth the data and extract these parameters. CYLEX measurements have proven to be useful in comparative studies of explosive formulations as well as warhead development because the geometry closely resembles that of most warheads [3]. Historically, however, the first 10–15 μs of information in these tests are ignored due to "complex behavior" [10] attributed to the interaction of the detonation front with the cylinder walls. Interest in studying detonations in new energetic materials as well as the incorporation of layered materials and liners to the system has led to new experiments that examine this regime in more detail [11,12]. Techniques more sensitive to measuring the early-time expansion behavior include Fabry-Perot interferometry [9], velocity interferometry system for any reflector (VISAR) [13] and glass prisms [12]. While in principle the streak records obtained in the CYLEX test also capture this interesting time regime where the shock wave is interacting with the cylinder wall, in practice the standardized analysis of the streak records is limited by a small number of data points, has poor resolution, and is hindered by human subjectivity and excessive variability. With the new found interest in studying the early-time expansion, and the hundreds of legacy records archived in laboratories around the world, there is an interest to develop a technique that can extract high-fidelity data from CYLEX streak records.

This paper describes the Air Force Research Laboratory's effort to improve the processing of CYLEX test streak records and to examine the early-time behavior of the expansion. To do this, modern digitization and image processing techniques were employed and a new formalism was developed to extract the displacement–time data from CYLEX film records. The result is a methodology that greatly increases the resolution of the data, removes human subjectivity, and reduces analysis time from hours to seconds. The availability of higher fidelity data prompted us to examine the deviations in the real expansion from Davis' empirical fitting equation [10]—the fitting function often used to fit the late-time expansion. With the aid of CTH hydrocode calculations, new fitting functions were developed to model both the early and late-time expansion data. These functions contain physically meaningful fitting parameters and include terms which estimate the intensity and time scales of the shock and gas induced expansion of the cylinder independently.

2 CYLEX Tests

The CYLEX test provides the time dependent position of the outside wall of an explosive filled cylinder during detonation by recording the silhouette of a slice of the cylinder viewed through a slit with a streak camera. Details of the setup and measurement of CYLEX test can be found in the original military standards [3]. The resulting streak record is recorded onto photographic film and contains two portions: a static fiducial used to calibrate the image spatially and a dynamic portion that captures the expanding cylinder wall in time.

Historically, the displacement data were extracted from the film records by eye with the aid of optical comparators. More recently, streak records have been digitized in grayscale and the data were taken from these images rather than the original film. Either way, the process took hours to complete for a single record, resulted in only about 50–100 data points per record, and was susceptible to human subjectivity.

In the new automated method, the streak records were digitized at 1200 dpi using a transmission-type film scanner in 256 grayscale. The resulting files are very large (> 100 MB) and are stored in an uncompressed digital format (tiff) so as to not lose any information. A convenient and efficient user-interface macro was written to import, calibrate, and analyze the digitized images using the IGOR PRO software package [14]. The heart of the macro is a cylinder-wall-finding subroutine which is based on the Shen-Castan Gaussian edge detection algorithm [15]. This particular edge detector was chosen due to its efficiency and relative insensitivity to noise [16]. In the streak images, the spatial resolution of the data approaches the grain size of the film, so it is critical to use an edge detection algorithm that is insensitive to grain-noise to achieve the maximum resolution. It is also critical that the spatial calibration and orientation of the record be performed in an equally precise manner. The digital methodology using edge finding algorithms is nearly automatic, is very reproducible, and extracts thousands of data points in about 1 min.

An example streak image is shown in Figure 1, containing the static fiducial (top quarter of image) and the dynamic expansion of the cylinder (bottom three-quarters of image). Overlaying the digitized streak record is the cylinder wall's edge obtained from the edge-finding subroutine. Approximately 8000 data points were extracted from each side of the cylinder, and the detail to the right clearly reveals complex acceleration and deceleration of the wall due to the shockwave interactions and reflection off the surface.

If appropriate film is used and the backlighting of the cylinder is sufficiently intense, the ultimate resolution of the extracted data is limited by the streak camera's slit width and the detonation velocity. For a vertical field of view of 6 mm at the cylinder, and a detonation velocity of 6 mm μs^{-1}, one estimates the time resolution to be approximately 1 μs, in approximate agreement with the observed time response of the data. A thorough analysis of the reproducibility and the temporal and spatial resolution of the Cylinder test have been performed and will be reported elsewhere [17].

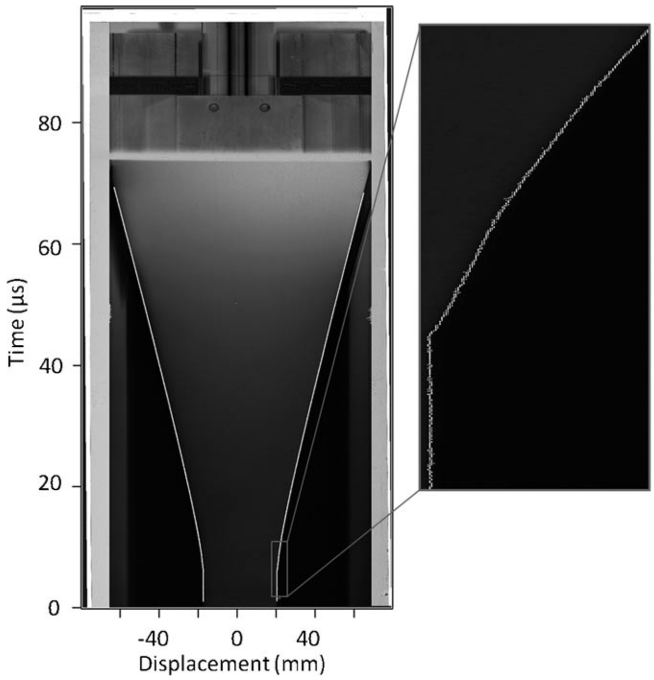

Figure 1. Example of a CYLEX streak record image of a high explosive in a 5.08 cm (2 in.) copper cylinder (left) with the detected edge artificially highlighted. An expanded portion of the first 10 μs of the expansion clearly shows effects of the shock waves interacting with the wall.

3 Results

Figure 2 plots the wall displacement versus time for the right and left side of a typical copper CYLEX test using the new analysis method. In this example, the left and right side expansion of the cylinder walls are nearly identical, indicating the uniformity of the expansion of the cylinder. This degree of agreement between the two sides is frequently *not* observed, and the difference is indicative of an asymmetry in the detonation, gas expansion, explosive fill, or cylinder material properties.

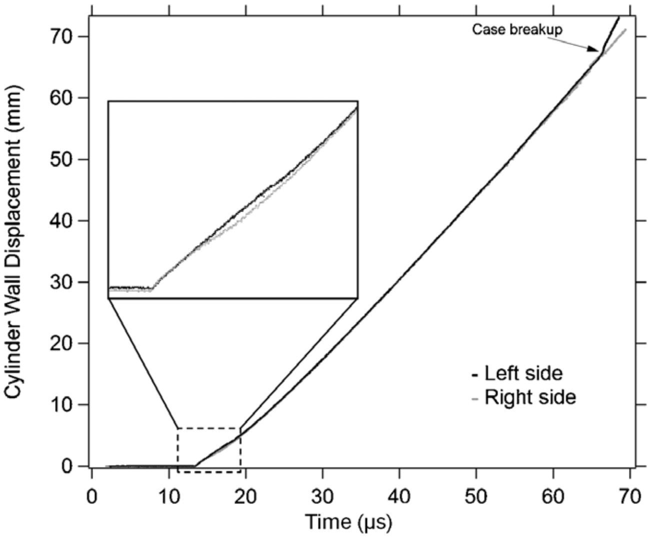

Figure 2. Cylinder wall displacement versus time for both the right and left sides of a 5.08 cm CYLEX test.

For most of the expansion in this example, the wall expands smoothly until approximately 65 μs when the copper case begins to break up. Upon closer inspection, the first few microseconds of the expansion are observed to be kinked. At $t_0 = 13.2$ μs, where the expansion begins, there is a discontinuity in the time derivative of the position of the wall (i.e., the velocity) indicating a very sharp acceleration of the wall, presumably due to a shock wave hitting the outside of the wall. A second, much weaker, kink is also observed at $t \sim 18$ μs.

To extract the parameters used for EoS or Gurney energy, the displacement versus time data are usually fit to a function. A variety of functional forms have been used in the past including polynomials [18], hyperbolas [19], and switching functions [10]. One of the simplest and most useful is Davis' equation [10], which is essentially a constant velocity that is turned-on with a switching function of order $t^{1/2}$:

$$r = V(t - t_0)\frac{\sqrt{t - t_0}}{\sqrt{t - t_0} + \sqrt{\tau_1}} \tag{1}$$

The displacement, r, in this model is a function containing only three fitting parameters, t_0, V, and τ_1, which can be physically interpreted as the expansion start time, the terminal cylinder wall velocity, and the time constant that describes the acceleration.

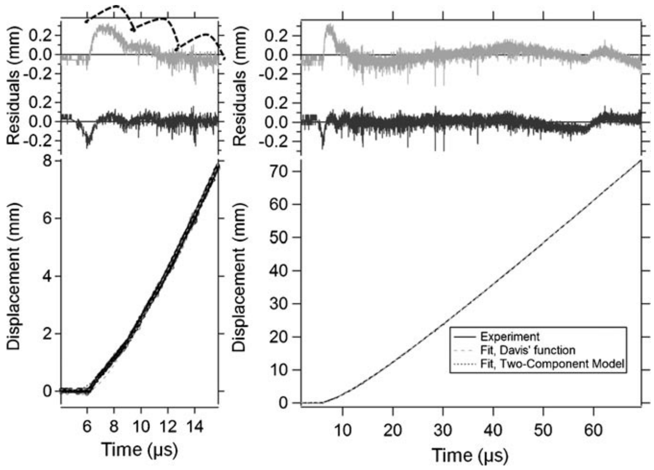

Figure 3. Results of fitting the outer wall displacement versus time data from a 5.08 cm (2 in.) CYLEX test to the Davis' equation (top residual trace) and the "two-component model" described in the text (lower residual trace). The bold dashed line above the residual on the left were added to emphasize the presence of reverberations, just beginning to be resolved in the data.

Figure 3 shows the fit of a high explosive in a 5.08 cm copper CYLEX test using Eq. (1) (dashed trace). Also shown is the residual of this fit (top trace) as well as the fit results for a new "two-component" model discussed below (lower residual trace). Equation (1) fits the data reasonably well except during the first 10 μs of the expansion. In the residual of this fit, several periodic expansions of the cylinder wall (emphasized with a bold dashed line) are observed with a period of ~2 μs. This period is consistent with the time scale that one would expect for a shock wave to reverberate within the copper cylinder wall with a thickness of 5.08 mm and suggests that this measurement may be beginning to resolve the effects of the shock wave interacting with the cylinder wall.

3.1 Hydrodynamic Modeling of the CYLEX Test

Even with the improved resolution provided by the automated data reduction, the periodic expansions in the first 10 μs are obscured by noise. To verify the assertion that we are beginning to observe the effects of the shock wave directly interacting with the cylinder wall with the CYLEX test, simulations of the test were performed using the CTH hydrocode [20–22]. The simulations were run in axially-symmetric, two-dimensional coordinates. The explosive was modeled with the JWL EoS and programmed burn, and the cylinder with the Mie-Grüneisen EoS. The dimensions of the cylinder were the same as the CYLEX test cylinder. Tracer points on the outer edge of the cylinder were used to obtain the expansion data in the radial direction, identical to what would be seen in a "higher-resolution" streak record.

Figure 4 shows the results of a CTH simulation of a 5.08 cm (2 in.) CYLEX test, including the acceleration, velocity, and position of the outer wall as a function of time after initiation of the explosive. Clearly observable in the acceleration and velocity traces are the complex series of shock induced expansion and release waves interacting with the outer wall of the cylinder. The resulting cylinder displacement function is consistent with what is observed in the CYLEX trace data.

3.2 Empirical Fitting Models of the CYLEX Test

The purpose of these CTH calculations is to provide insight on the mechanisms involved in the expansion of the cylinder wall and to guide us to develop a physically meaningful empirical function to fit the entire CYLEX. While the behavior observed in the simulations is too complex to capture exactly, to a very good approximation what is observed are three distinct forces acting on the wall of the cylinder [23]:

(a) A periodic and decaying train of shock *accelerating* impulses.
(b) A periodic and decaying train of shock *decelerating* impulses.
(c) A single, very weak, but sustained accelerating impulse due to the gas expansion.

In this particular simulation, the characteristic period for (a) and (b) was ~2 μs and exhibited a decay with a time constant ~8 μs. The impulse widths for (a) and (b) were significantly different, showing a full width at half maximum ~0.3 and ~1 μs, respectively. The decay in intensity for feature (c) was much longer with a time constant on the order of 25 μs.

The train of shock-induced accelerating/decelerating impulses can each be approximated with a series of decaying Gaussian functions and the force due to the gas expansion can be approximated by a double exponential function:

$$\ddot{r} = \sum_{n=0} \frac{I_\mathrm{a}}{r^n_\mathrm{shock}} \mathrm{e}^{\frac{-(t-t_0-nt_\mathrm{rev})^2}{\tau_\mathrm{a}^2}} - \sum_{n=0} \frac{I_\mathrm{b}}{r^n_\mathrm{shock}} \mathrm{e}^{\frac{-(t-t_0-nt_\mathrm{rev})^2}{\tau_\mathrm{b}^2}} + I_\mathrm{c}\left(\mathrm{e}^{-(t-t_0)/\tau_{\mathrm{c}2}} - \mathrm{e}^{-(t-t_0)/\tau_{\mathrm{c}1}}\right) \quad (2)$$

Gaussian functions were used to model each impulse since they are well-behaved and integrable functions and approximate the shape of the impulse reasonably well. Integration of this Eq. (2) with respect to time twice gives the cylinder wall displacement as a function of time. This "three-force model" contains ten parameters: the expansion start time (t_0), the shock reverberation period (t_rev), the shock train decay rate (r_shock), the shock impulse widths (τ_a and τ_b), the amplitude of the shock impulses (I_a and I_b), the gas expansion amplitude (I_c), and the rise and fall time constants for the gas expansion ($\tau_{\mathrm{c}1}$ and $\tau_{\mathrm{c}2}$). Each of these parameters has a physical meaning and, in principle, can be estimated knowing the system's physical properties such as the dynamic acoustic impedance of the materials, the sizes of the materials, and the CJ pressure of the detonation products.

Figure 5 depicts the time dependence of the wall acceleration profiles due to the three forces described above. Their sum (bottom trace) is a complex function that approximates the acceleration profile observed in the CTH simulations. Fitting of the simulation data effectively parameterizes the results and facilitates the interpretation of the simulation in terms of physically meaningful parameters. Further, it provides an easy means to compare simulations of different systems. Overlaying the CTH simulation in Figure 4 are the fits of the acceleration, velocity, and displacement curves using the three-force model. While not perfect, the model captures the most prominent features of the simulation, most notably the peaks and valleys of the first few reverberations.

Unfortunately, Eq. (2) is too complicated to fit the CYLEX test data directly because many of the time components are not resolved. As mentioned above, the experimental resolution is on the order of 1 μs, however, the features observed in the CTH simulations occur on timescales about three to ten times shorter. At lower temporal resolution, the first two forces (a) and (b) cannot be separated out, nor can their impulse widths, τ_a and τ_b, be deduced.

To consider what a lower resolution function would look like, it is instructive to examine the first and second integrated functions (i.e., the velocity and displacement

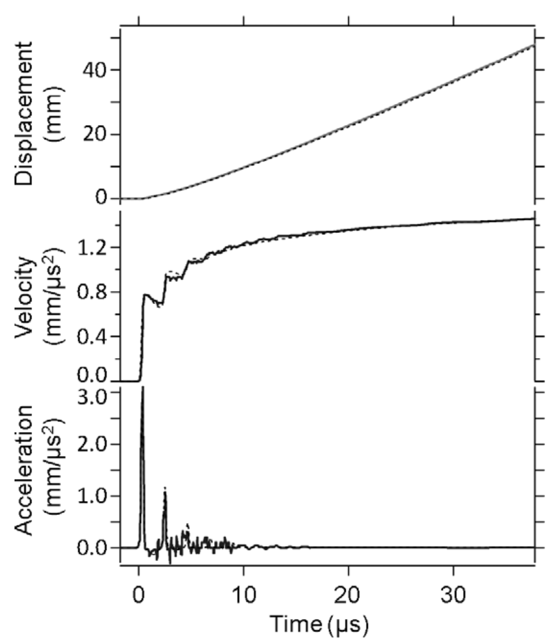

Figure 4. Results of CTH simulations of a 5.08 cm (2 in.) CYLEX test (solid) overlaid with the fits (dashed) to the "three-force model" described by Eq. (2). While not perfect, the model captures the most prominent features of the simulation and reproduces the displacement curve extremely well.

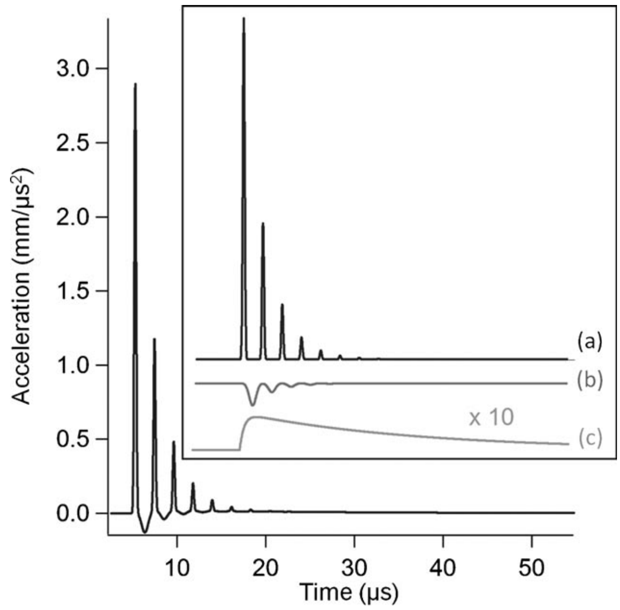

Figure 5. Acceleration profile from the "three-force model" of the CYLEX expansion (bottom trace). Also depicted are the individual components of the model (inset) as defined in Eq. (2).

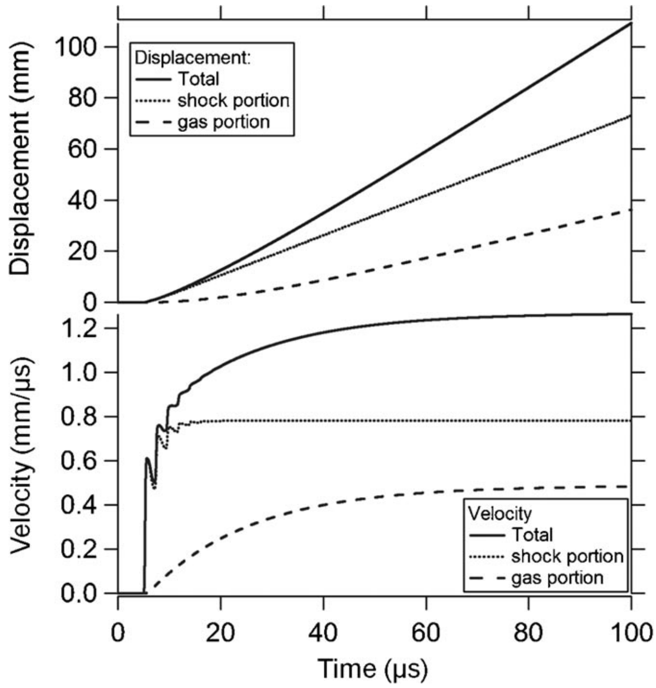

Figure 6. Velocity and displacement profiles from the three-force model fitted to the CTH results. The solid lines show the total predicted values from integrating Eq. (2), whereas the dotted lines are the integrals of only the "shock" related terms and the dashed lines are the integrals of the "gas" related terms.

functions) of Eq. (2) and to decompose them into a "shock" component (i.e., from forces (a) and (b)) and a "gas" component (from force (c)). Figure 6 depicts the decomposed functions, the dotted traces corresponding to the shock related terms and the dashed traces corresponding to the gas related terms. Ignoring the high-frequency oscillations in the data, the shock portion of the expansion can be modeled as imparting a constant velocity on the cylinder wall that is switched on with a time constant ~3–5 μs. This effectively treats the periodic forces (a) and (b) as a single impulse which decays with an observable time constant. The remaining portion of the expansion due to the gas expansion should be fully resolvable and thus is the twice integrated double exponential function from Eq. (2).

These simplifications to the three-force model suggest a new fitting function for displacement–time data obtained from the CYLEX test:

$$r = V_{\text{shock}}\left((t-t_0) - \tau_{\text{shock}}\left(1 - e^{-\frac{t-t_0}{\tau_{\text{shock}}}}\right)\right) + I_{\text{gas}}\left(\tau_2^2 e^{-\frac{t-t_0}{\tau_2}} - \tau_1^2 e^{-\frac{t-t_0}{\tau_1}} + (\tau_2-\tau_1)(t-t_0) + (\tau_1^2-\tau_2^2)\right) \quad (3)$$

This "two-component model" (i.e., a "shock" and a "gas" component) contains only six parameters. In addition to the time 0 (t_0), there is a shock-induced wall velocity (V_{shock}) that switches on with a time constant (τ_{shock}), rise and decay time constants for the gas impulse (τ_1 and τ_2), and the amplitude of the gas impulse (I_{gas}).

Figure 3 shows the results of applying Eq. (3) to a high explosive CYLEX test (lower residual trace). The fit captures all of the prominent features of the data, eliminating the early time impulse missed in the fit using Eq. (1) (top residual trace). It also captures more accurately the late-time curvature out to 40 μs after which the deviations are probably due to case failure. As mentioned above, Eq. (3) assumes that the individual reverberations are unobservable and thus does not include parameters that can model them. However, from the residuals, those reverberations are just barely observed with a signal-to-noise ratio of about 2. If higher sensitivity, higher temporal resolution CYLEX data is obtained, the results should be analyzed using the full three-force model with Eq. (2) which can capture the details of the reverberations.

4 Discussion

Parameterizing CYLEX data or hydrocode simulations with either of these two models allows us to separate the roles that the forces' shock induced work and the *PdV* work have on the expansion. The relative amount of work done by each process can be determined by twice differentiating the displacement of each component with respect to time and then integrating the result with respect to the total displacement:

$$\frac{W_{\text{shock}}}{W_{\text{gas}}} = \frac{\int_0^\infty \frac{d^2 r_{\text{shock}}}{dt^2}\, dr_{\text{total}}}{\int_0^\infty \frac{d^2 r_{\text{gas}}}{dt^2}\, dr_{\text{total}}} \quad (4)$$

where r_{shock} and r_{gas} are the time-dependent displacement functions of the shock and the gas contributions to the total displacement (r_{total}) of the cylinder wall. This ratio can be calculated numerically once the fitting parameters have been determined for either model presented above. For the CTH hydrocode data shown in Figure 4, we find that for the three-force model (Eq. 2) the ratio $W_{shock}/W_{gas}=1.53$. This value suggests that the work done by the shockwave accounts for a significant portion of the total work on the cylinder [24].

Since the work done by the shockwave is likely to be sensitive to the reverberation decay rate and periodicity, it is reasonable to expect that the ratio of W_{shock}/W_{gas} will be affected by changes in the impedance of the various materials in the cylinder as well as their thicknesses. To test this hypothesis, we examined the data from a series of CYLEX tests that had polymer-based liners inserted within the copper cylinder. In these tests, the copper cylinder diameter and thickness were kept fixed at the standard dimensions, and tests with liners of thickness 4.8 and 8.0 mm were compared to a test without a liner. The liner material was located against the copper wall in place of some of the high explosive. The resulting CYLEX data are plotted in Figure 7. In addition to reducing the total energy of the system when some of the high explosive is replaced with polymer (evident by the reduced asymptotic velocity), there are clear qualitative changes in the early time expansion as well. After fitting each of these datasets to Eq. (3), the ratio W_{shock}/W_{gas} was found to be 2.10, 1.63, and 1.25 for the liner-less, 4.8 mm, and 8.0 mm lined cylinders, respectively. While certainly not conclusive given the small number of tests, these results are at least consistent with the notion that the liner affects the partitioning of energy between the "shock" (i.e., forces (a) and (b)) and "gas" (i.e., force (c)) induced expansion of the cylinder wall. Further testing of this idea is clearly needed.

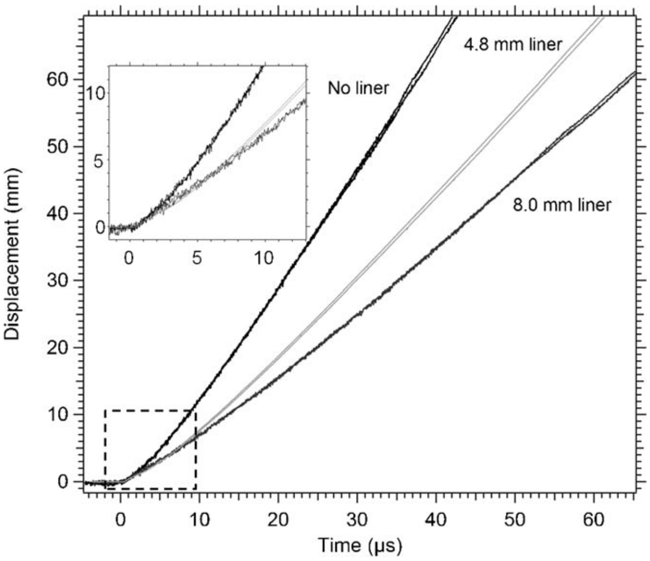

Figure 7. Comparison of the displacement profiles from cylinders with and without liners. The two traces present for each profile were taken from the left and right sides of the same test.

5 Conclusion

In summary, modern digital imaging processing techniques were adapted to the analysis of CYLEX streak records. This new methodology is efficient, takes significantly less time to perform than previous methods of analysis, drastically increases the quality and quantity of data extracted from a film record, and virtually eliminates human subjectivity during the analysis. The higher quality of the data has motivated us to develop new fitting models for CYELX data aimed at capturing both the early-time and late-time features. With the aid of CTH hydrocode simulations, two new functions were developed that can have physically meaningful fitting parameters. The first function models the expansion as a sum of three-forces and replicates the dominant reverberations in the cylinder wall during the expansion. The second "two-component" model is a simplification of the three-force model and was developed to fit data which does not fully resolve the fast reverberation behavior. Either model can be used to parameterize the results of simulations or experimental data and enables a more detailed interpretation of the results. Results of applying these models to lined and un-lined CYLEX tests suggest that the shock induced expansion of the cylinder wall plays an important role in the overall expansion and that presence of a liner in the system geometry may affect the partitioning of energy between the shock and gas stages of the expansion.

Acknowledgements

We are indebted to Yasuyuki Horie and Lalit Chhabildas for many valuable discussions and encouragement in pursuing this work.

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[23] It is important to point out that we are interpreting the forces (a) and (b) as due exclusively to work done by the shock wave and force (c) as due to the PdV work. This interpretation needs to be tested. Throughout this paper when we refer to "shock" parameters and "gas" parameters, we are actually referring back to these forces. It is likely that these forces are actually a convolution of both PdV and shock work and therefore care must be taken in interpreting the results of the fits too literally.
[24] We reemphasize that this assertion assumes that forces (a) and (b) are exclusively due to the shock and that force (c) is exclusively due to the gas. This is likely an over simplification and needs to be tested.

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